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AGN accretion disks as spatially resolved by polarimetry

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Abstract.

A crucial difficulty in understanding the nature of the putative accretion disk in AGNs is that some of its key intrinsic spectral signatures cannot be observed directly. The strong emissions from the broad-line region (BLR) and the obscuring torus, which are generally yet to be spatially resolved, essentially 'bury' such signatures. Here we argue that we can actually isolate the disk emission spectrum by using optical and near-infrared polarization of quasars and uncover the important spectral signatures. In these quasars, the polarization is considered to originate from electron scattering interior to the BLR, so that the polarized flux shows the disk spectrum with all the emissions from the BLR and torus eliminated. The polarized flux observations have now revealed a Balmer edge feature in absorption and a blue near-infrared spectral shape consistent with a specific and robust theoretical prediction. These results critically verify the long-standing picture of an optically thick and locally heated disk in AGNs.

1. The key buried signatures from the central accretion disk

The primary radiative output of active galactic nuclei (AGNs) is observed at the ultraviolet/optical wavelengths. This is attributed to be from an accretion disk around a supermassive black hole. While this putative accretion disk has been modeled extensively, it is well known that there are disagreements between observations and model predictions in a few major respects (e.g. refs. [1, 2]). A crucial observational difficulty here has been that we still do not have enough spatial resolution to isolate the accretion disk from the surrounding regions. Important spectral features of the disk are thus often buried under the strong emission from these regions — in particular, from the broad-line-emitting region (BLR) and from a slightly larger-scale torus-like region with hot dust grains.

One such key spectral region is the near-infrared. In the fundamental hypothesis of the standard, most extensively studied model [3], the disk is optically thick and heated by local energy dissipation, and this sets the effective disk temperature T as a function of radius r as

$T \propto r^{-3/4}$ over a broad range of radii. This leads to the well-known blue spectral shape at long wavelengths, $F_\nu \propto \nu^{+1/3}$, in the simple case of local blackbody emission. In more sophisticated, bare-disk atmosphere models (e.g. ref. [4]), the same blue limit is reached longward of $\sim 1 \mu\text{m}$ essentially independent of parameters suitable for quasars. Then we should be able to robustly test disk models here. Furthermore, the standard disk is also well known to be gravitationally unstable in the outer radii [5], which may correspond to those emitting in the near-infrared [6]. The spectrum may show a break due to a possible disk truncation and become even bluer toward longer wavelengths. Thus the near-infrared disk spectrum is quite important for the tests of disk models. However this is almost exactly where the dust thermal emission from the torus starts to dominate the spectrum (set by dust sublimation temperature). Thus this important near-infrared disk spectrum usually cannot be observed.

Another key spectral signature is the Balmer edge. Among the opacity edge features generally predicted by disk atmosphere models, the Balmer edge has the advantage (over the Lyman edge) of being much less prone to foreground absorptions. However, high-order Balmer emission lines and Balmer continuum (and also FeII blends) from the BLR bury the Balmer edge feature in the disk spectrum making it essentially unobservable.

However, we argue here that we can separate the disk emission from the surrounding emissions by using optical and near-infrared polarization of quasars. With this measurement, effectively gaining very high spatial resolution, we can study these key spectral signatures from the accretion disk.

2. The optical polarization of quasars or Type 1 AGNs

Perhaps the most well-known optical polarization in AGNs is the one seen in Type 2 objects, where the torus obscures our line of sight to the accretion disk and the BLR. The broad emission

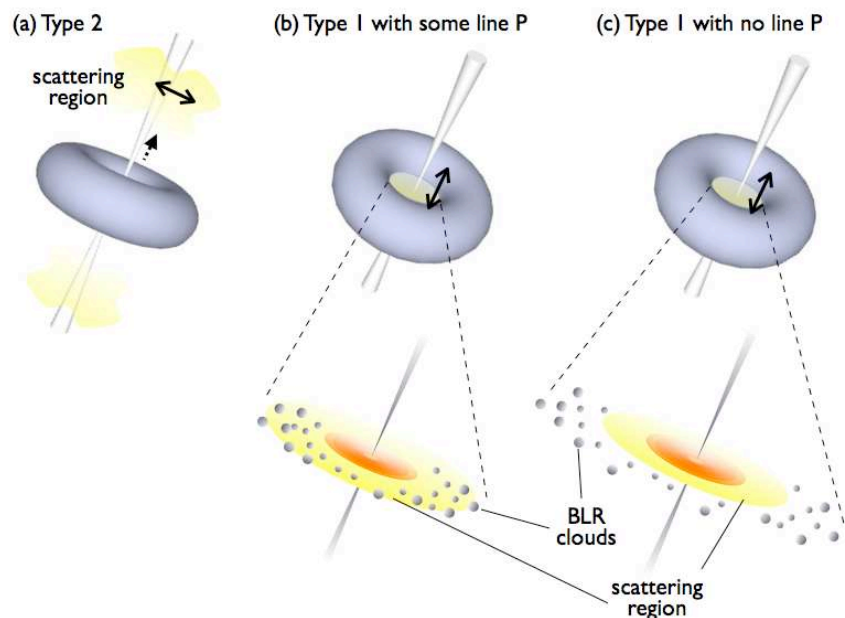


Figure 1. Schematic diagrams for the geometry of dominant scattering regions for (a) Type 2s (b) Type 1s with some line polarization (c) Type 1s with no line polarization. In each panel, the double arrow shows the position angle of continuum polarization.

lines are seen in the polarized flux in many of these, with polarization position angle (PA) perpendicular to the radio jet axis [7]. The interpretation is that the gas which resides *outside* the BLR, along the jet axis above and below the torus, scatters the light from the accretion disk *and* the BLR into our line of sight (Fig.1a). Thus they both show up in the polarized flux.

Here we are interested *not* in these Type 2 objects, but rather in Type 1 objects, namely Seyfert 1 galaxies and quasars. In those objects, our line of sight is much less inclined, giving a direct view of the bright nuclear region interior to the torus. This gives rise to a different nuclear polarization component to dominate. The optical continuum is often polarized at polarization degrees P of $\lesssim 1\%$ level, with PAs *parallel* to the jet axis (e.g. ref.[8]). In many Seyfert 1s, the broad lines are also polarized but often at lower P and at different PA than continuum (it rotates across the line wavelengths; e.g. ref.[9]). These imply that the scattering region is more or less similar in size to the BLR. The parallel polarization quite possibly indicates that the scattering region is in a flattened/equatorial optically-thin geometry having its symmetry axis along the jet direction (Fig.1b).

At least in some quasars, however, similar continuum polarization is seen but with no or very little line emission in the polarized flux. In this case, scattering is considered to be caused *interior* to the BLR (Fig.1c), by electrons (since the site is inside the dust sublimation radius). Then the polarized flux would in fact be an electron-scattered copy of the intrinsic spectrum of the central engine, with all the emissions from the BLR and torus eliminated. This polarized flux enables us to isolate the accretion disk spectra from the contaminating emissions.

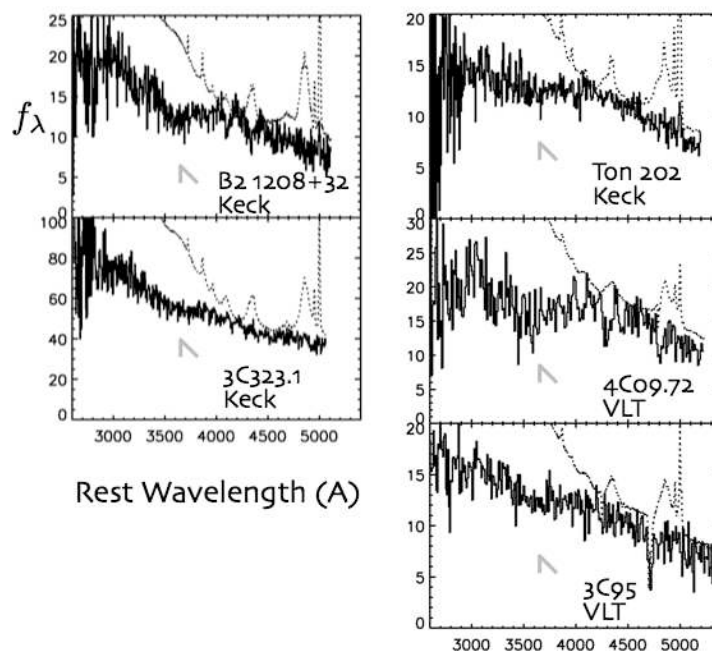


Figure 2. Optical spectropolarimetry of five quasars from ref.[10]. The solid line is the polarized flux in units of 10^{-18} ergs/cm²/sec/Å. The dotted line is the total flux scaled to match the polarized flux at the red side. The wavelength of the Balmer discontinuity, 3646Å, is indicated as a folded line in each panel.

3. Intrinsic disk spectra as revealed by polarimetry

Figure 2 shows the polarized flux spectra of such quasars. In contrast to the total flux spectra, we see essentially no emission lines in the polarized flux spectra. Thus the polarized flux is very likely to show the intrinsic spectral behavior of the disk without the BLR emission contamination. The objects were chosen to be at redshift $\gtrsim 0.3$ to make sure that the Balmer edge region is covered with good sensitivity. The feature is indeed seen, all in absorption: there is a downturn at around 4000\AA and an upturn at around 3600\AA in all the objects shown. Thus the fundamental implication here is that the emission is thermal and optically thick in nature.

Then we have extended the work to longer wavelengths: since the polarization originates interior to the dusty torus, we should also be able to eliminate the dust emission and uncover the underlying near-infrared disk spectrum. Figure 3 shows the results for six quasars [11, 17]. Some of the quasars are those shown in Figure 2, while the others have newly been found to be suitable for this work (i.e. no or very little line flux in polarized light) from our optical polarimetric survey with the ESO3.6m telescope and follow-up spectropolarimetry with the VLT [11]. In all six objects, the total flux spectra in νF_ν show an up-turn longward of $\sim 1\text{ }\mu\text{m}$ due to the onset of dust emission. However, the polarized flux spectra all show systematically a

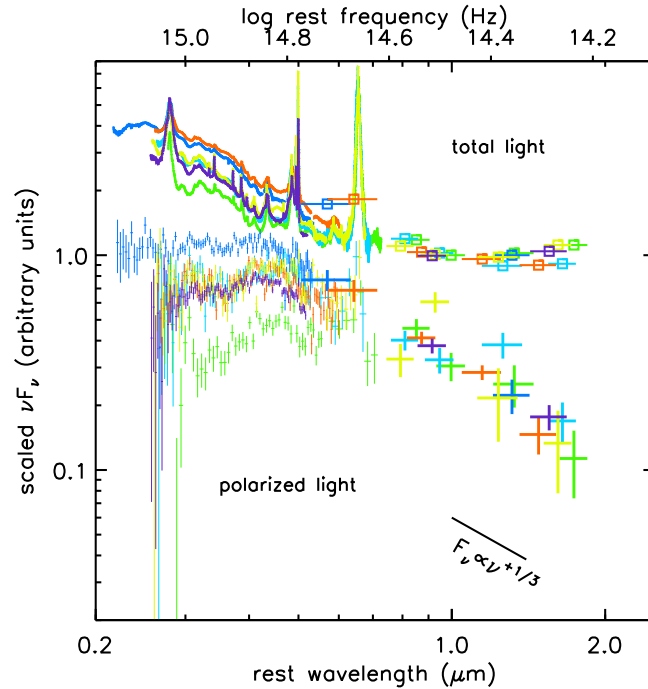


Figure 3. Overlay of the polarized and total flux spectra observed in six different quasars, from ref.[11]. We plot scaled νF_ν data: Q0144-3938 (redshift $z=0.244$), green; 3C95 ($z=0.616$), blue; CTS A09.36 ($z=0.310$), light blue; 4C 09.72 ($z=0.433$), red; PKS 2310-322 ($z=0.337$), light green; Ton 202 ($z=0.366$), purple. Total flux spectra, shown as bold traces in the optical and as squares in the near-infrared, are normalized at $1\mu\text{m}$ in the rest frame, by interpolation. Polarized flux spectra, shown as light points in the optical and as bold points in the near-infrared (vertical error bars, $1-\sigma$), are separately normalized, also at $1\mu\text{m}$, by fitting a power-law to the near-infrared polarized flux spectra. The normalized polarized flux spectra are arbitrarily shifted downwards by a factor of three relative to the normalized total flux spectra, for clarity.

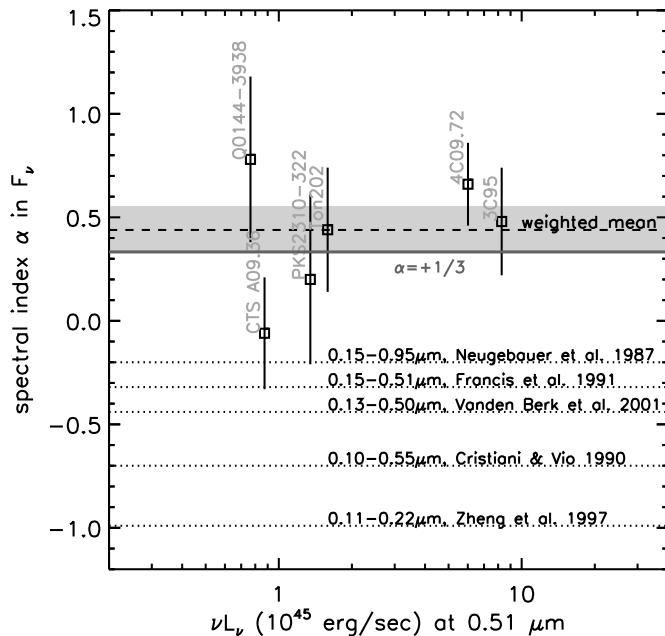


Figure 4. Spectral index of polarized flux spectra, from ref.[11]. We plot α (in $F_\nu \propto \nu^\alpha$) against νL_ν for total light at $0.51 \mu\text{m}$. The index was measured by a power-law fit for each near-infrared polarized flux spectrum (note the different wavelength range covered depending on the redshift) and is shown with $1-\sigma$ error bars. A weighted mean of the spectral index measurements is shown dashed; the shaded area represents its deduced $1-\sigma$ uncertainty. The mean or median slopes of the ultraviolet/optical total flux spectra derived in various studies [12–16] are also shown.

rapid decrease toward long wavelengths with a shape of approximately power-law form. The spectral indices α measured in $F_\nu \propto \nu^\alpha$ for the near-infrared polarized flux are shown in Figure 4, and compared with those observed at the optical/ultraviolet wavelengths. The uncovered near-infrared colors are clearly much bluer than those at the shorter wavelengths. Surprisingly they are all consistent with the shape $\nu^{+1/3}$, with an weighted mean of $\alpha = +0.44 \pm 0.11$.

The systematic behavior of the polarized flux, and the fact that PAs are observed to be essentially constant over the whole wavelengths (from the ultraviolet to near-infrared) in each object [11], strongly argue against there being any secondary polarization component arising in the near-infrared. Therefore, the near-infrared polarized flux spectra are very likely to reveal the intrinsic spectra of accretion disks. The measured slopes, which are as blue as the predicted spectral shape of $\nu^{+1/3}$, strongly suggest that, at least in the outer near-infrared emitting radii, the standard but unproven picture of the disk being optically thick and locally heated is approximately correct. In this case, other model problems at shorter wavelengths should be directed to the lack of our understanding of the inner regions of the same disk.

4. Outlook

The optical and near-infrared polarization measurements of quasars have turned out to be quite revealing, and have been delineating the fundamental aspects of the accretion disk in their central engine. A further question is: does the revealed near-infrared spectrum show an indication of disk truncation in this outer region? Although statistically insignificant, the data do suggest that the slope is slightly bluer than the shape $\nu^{+1/3}$. Theoretical modeling is underway with the current data. Further measurements may provide totally new insight on the outer edge of the disk and how material is being supplied to the nucleus.

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